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EVALUATION OF *STRIGA*-RESISTANT EARLY MAIZE HYBRIDS AND TEST LOCATIONS UNDER *STRIGA*-INFESTED AND *STRIGA*-FREE ENVIRONMENTS

R.O. AKINWALE, B. BADU-APRAKU[1] and M.A.B. FAKOREDE
Obafemi Awolowo University, Ile-Ife, Nigeria
[1]International Institute of Tropical Agriculture (UK) Limited, Carolyn House, 26 Dingwall Road, Croydon, CR9 3EE, UK
Corresponding author: b.badu-apraku@cgiar.org

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ABSTRACT

Emergence of several seed companies in the West Africa sub-region during the last decade has necessitated intensified efforts towards hybrid development and extensive testing. The objectives of the present study were to evaluate selected *Striga*-resistant maize (*Zea mays* L.) hybrids for grain yield and stability of performance based on multiple traits. Thirty *Striga*-resistant single–cross maize hybrids plus two checks were evaluated under artificial *Striga* infestation and *Striga*-free conditions at 2 locations in Nigeria in 2008 and 2009. The two test locations possessed high discriminating ability. More promising genotypes were identified under *Striga* infestation based on multiple traits than based on yield *per se*, suggesting that grain yield alone is not a precise predictor of *Striga* resistance. Based on both biplot analyses, TZEI12 x TZEI25 was identified as the most outstanding in performance under both research conditions. Furthermore, TZEI11 x TZEI127 and TZEI80 x TZEI2B were identified as the most outstanding under *Striga*-infested conditions and TZEI60 x TZEI87 under *Striga*-free conditions by the two biplot methods. The hybrids with outstanding performance should undergo extensive multilocational testing and promotion for adoption for commercial production.

Key Words: GGE biplot, multiple traits, *Zea mays*

RÉSUMÉ

L'émergence de plusieurs companies de semence dans la sous région weste africaine durant la dernière decades a nécessité des efforts intensifiés en développement d'hybrides et essais extensifs. Les objectifs de la présente étude étaient d'évaluer des hybrides sélectionnés de maïs (*Zea mays* L.) résistants au striga pour le rendement en grains et la stabilité de sa performance sur base de multiples traits. Trente hybrides de maïs résistants à un seul croisement ainsi que deux témoins étaitent évalués en condition artificielle d'infestation et dans des conditions sans *Striga* dans deux milieux du Nigeria en 2008 and 2009. Les deux milieux en tests possedaient une aptitude discriminatoire élevée. Plus de génotypes promettants étaient identifiés en condition d'infestation du *Striga*, en se basant sur des traits multiples plutôt que sur base du rendement, suggérant que seul le rendement en grain n'est pas un prédicteur précis de la résistance du *striga*. Basé sur les analyses biplot, TZEI12 x TZEI25 était identifié comme le plus remarquable en performance sous conditions de recherche. En plus, TZEI11 x TZEI127 et TZEI80 x TZEI2B étaient identifies comme étant les plus remarquables en conditions d'infestation du *Striga* et TZEI60 x TZEI87 sous conditions non infestées du *Striga* par deux methods biplot. Des études extensives multilocales des hybrides à performance remarquable ainsi que la promotion de l'adoption pour une production commerciale sont recommendées.

Mots Clés: GGE biplot, traits multiples, *Zea mays*

INTRODUCTION

Maize *(Zea mays* L.*)* is a major staple food crop in sub-Saharan Africa. Its high energy content has made it very important in human and animal diets. There is a high incidence of the parasitic weed, *Striga hermonthica* (Del.) Benth in the savanna ecology of Nigeria considered as the maize belt. *Striga,* therefore, constitutes a major threat to the achievement of the full yield potential of maize in the savannas of Nigeria. *Striga* spp. are estimated to infest severely 40 million hectares of cereal crops in the tropics and another 70 million hectares have moderate levels of infestation (Lagoke *et al*., 1991). Annual cereal yield losses from *Striga* in the savanna regions alone account for US $7 billion and are detrimental to the lives of more than 100 million Africans (M'Boob, 1986). Kim (1991) reported an average yield reduction by *Striga* on susceptible maize plants as 67% with a range of 41 – 91%.

Several *Striga* control measures including the use of N fertiliser, crop rotation, intercropping, and herbicide control have been proposed. However, host-parasite resistance is still considered the most economical, effective, and environmentally sustainable approach for controlling *Striga* in Africa (Parkinson *et al.,* 1989; Kim, 1991). In an effort to control *Striga* through host-plant resistance, the International Institute of Tropical Agriculture (IITA) has developed many inbred lines that combine earliness with resistance to *Striga* using backcrossing, hybridisation, and the S_1 family recurrent selection methods.

The development and cultivation of hybrid maize have been described as one of the greatest accomplishments of plant breeding in the twentieth century (Hallauer and Miranda, 1988). Hybrid development is a promising avenue to enhance maize yield potential in West and Central Africa WCA. Presently, there is an increase in the demand for hybrid seed in the sub-region as a result of the emergence of several new seed companies. The value of a hybrid is largely dependent on its yield performance and stability across test environments, when evaluated in multiple locations over years. The agronomic performance of a single-cross hybrid is greatly influenced by environmental factors prevalent during the growing season. The effect of genotype x environment interaction (GEI) in the evaluation of genotypes is of great importance to a breeder because it provides information on the adaptation and stability of the hybrids. In a multi-location trial, differences in the genotypes' ranking in various test locations hinder the identification of superior, stable hybrids (Epinat-Le Signor *et al.*, 2001). The presence of biotic and/or abiotic stresses compounds the GEI effects probably due to the complexities in the genetics of resistance/tolerance of the genotypes to the stress. When selecting hybrids for wide adaptation, breeders consider a noncrossover GEI or preferably absence of GEI.

Two test locations, Mokwa (9^{0}182 N 5^0 402 E, 457 m altitude, 1100 mm rainfall) and Abuja (9^0 162 N 7^0 202 E, 300 m altitude, 1500 mm rainfall) have been routinely used for the evaluation of maize genotypes for *Striga* resistance in the IITA Maize programmes. The two locations fall within the same agro-ecological zone, the southern Guinea savanna, suggesting that they may be classified into the same mega-environment. However, results of the "no scaling" genotype main effect, plus genotype-by-environment interaction (GGE) biplot analysis of the performance of early maturing varieties at the two locations, revealed different vertex cultivar for each location under *Striga* infestation and *Striga*-free conditions (Badu-Apraku *et al*., 2008). This result suggests that the two locations may not belong to the same mega-environment and that the information obtained on the genotypes from these two locations was not similar. There is, therefore, need to assess the uniqueness of the two test environments for evaluating genotypes for *Striga* resistance.

Even though grain yield improvement is the ultimate goal of most breeding programmes, a maize cultivar does not gain wide acceptance for cultivation by farmers just on the basis of its yield potential; but as a package of several other desirable attributes. A new maize cultivar must possess the minimum criterion established by the objectives of the breeding programme as well as other desirable agronomic and end user-preferred traits. If the genotype fails to meet the minimum criterion for any breeding objective, this will result in non-adoption of the genotype by farmers and consumers. This has prompted the identification of superior genotypes in the IITA Maize Improvement programme based on multiple traits (Badu-Apraku *et al*., 2010a, 2011b; Badu-Apraku and Akinwale, 2011). Badu-Apraku *et al*. (2011b) reported that under drought stress, selection of superior genotypes based on yield performance of early maize cultivars was consistent with that based on multiple traits; whereas the contrary was true under low-N stress. However, there is lack of information on the effectiveness of selection of genotypes based on grain yield performance *per se* as compared to selection for superior performance based on multiple traits under *Striga* infestation.

Analysis of variance procedure is useful for estimating the existence and magnitude of GEI; however, variance components alone do not provide satisfactory explanation for GEI (Domitruk *et al*., 2001). Several statistical tools have been proposed and used to estimate the performance and stability of a cultivar. Among the most powerful methods is the genotype main effect plus genotype-by-environment interaction (GGE) biplot, which has been increasingly utilised for analysing multi-environment trial MET data. The GGE biplot is based on environment-centered data, which removes the environment main effect and integrates the genotypic main effect with the genotype-by-environment interaction effect of a genotype-by-environment dataset (Yan *et al.,* 2000). It has been widely used for evaluating genotypes for high yielding ability and stability across environments (Badu-Apraku *et al*., 2008; Badu-Apraku and Lum, 2010; Badu-Apraku *et al*., 2010b), as well as for evaluating environments with a view of classifying them into mega-environments (Setimela *et al*., 2007; Badu-Apraku *et al*., 2011c). In all these studies, “no scaling” method of GGE biplot which is most appropriate for a wide range of environments, not within the same mega-environment was employed.

Test environment and genotype evaluations are meaningful only within a mega-environment (Yan *et al*., 2007). Yan and Holland (2010) reported that the most appropriate GGE biplot scaling method for simultaneous evaluation of genotype as well as test environment is the heritability-adjusted (HA) GGE biplot. This is based on the principle established by Allen *et al.* (1978), which stated that the proper measure of the value of a test environment is $r\sqrt{H}$, where r is the correlation between genotypic performance in the test environment and the target environments and $H = h^2$ is the heritability in the test environment.

Yan and Holland (2010) demonstrated that the vector length of an environment in the HA-GGE biplot approximates the square root of the heritability ($\sqrt{H}$) within the environment and that the cosine of the angle between the vectors of two environments approximates the genetic correlation (r) between them. Also, projections of test environment vectors onto that of the average environment approximate values of $r\sqrt{H}$. The length of the projections is proportional to the predicted genetic gain expected in the target environment from indirect selection in the test environments at a constant selection intensity. The authors also showed that HA-GGE is more appropriate GGE biplot for genotype evaluation because it weights information from the different environments proportional to their within-environment square root of the heritability.

Apart from being widely used in the analysis of genotype by environment data, GGE biplot software is an effective statistical tool for identifying genotypes with superior multiple traits that could be useful as parents in a breeding programme (Yan and Rajcan, 2002; Yan and Kang, 2003; Badu-Apraku *et al*., 2010a, 2011b; Badu-Apraku and Akinwale, 2011). In the GT biplot analysis, a standard deviation-standardised (SD) GGE biplot is usually employed to remove any bias that may be due to the different units in which the traits were measured and increase the convergence among traits.

The objective of the present study were to evaluate the performance of selected *Striga*-resistant hybrids based on their yielding ability and stability across environments using HA-GGE biplot; assess the performance of the hybrids on the basis of multiple traits using SD-GGE biplot; and assess the usefulness and uniqueness of the test locations routinely used for evaluating genotypes for *Striga* resistance by the IITA maize programme.

MATERIALS AND METHODS

Germplasm and field management. Thirty out of 378 early maturing hybrids (15 white- and 15 yellow-grained) were selected from a diallel study using a base index computed as I = [(2 x YLI) + EPP – (STRA8 + STRA10) – 0.5 (STRC8 + STRC10)], where YLI was yield of *Striga* infested plots, EPP was the number of ears at harvest in the *Striga*-infested plots, STRA8 and STRA10 were *Striga* damage ratings at 8 and 10 WAP, STRC8 and STRC10 were number of emerged *Striga* plants at 8 and 10 WAP. An early maturing *Striga* resistant elite variety and an intermediate maturing *Striga* susceptible hybrid were included as checks. The 30 hybrids, plus the two checks, were evaluated separately under artificial *Striga* infestation at Mokwa (9^{0}182 N 5^0 402 E, 457 m altitude, 1100 mm rainfall) and Abuja (9^0 162 N 7^0 202 E, 300 m altitude, 1500 mm rainfall) in the southern Guinea savanna of Nigeria in 2008 and 2009.

A randomised complete block design, with two replicates, was used in each trial. Each experimental unit was evaluated in two-row plots, 5 m long, spaced 0.75 m apart with 0.4 m between hills. Three maize seeds were sown per hill and thinned to two plants per hill two weeks after planting, to obtain a final population density of 66,000 plants ha^{-1}. The *Striga* infestation technique developed by the IITA Maize Improvement Programme was used to ensure uniform *Striga* infestation (Kim, 1991).

Striga hermonthica seeds were collected from sorghum fields in the preceding season and stored for at least six months before use. To stimulate suicidal germination of existing *Striga* seeds in the field, ethylene gas was injected into the soil before artificial infestation. The *Striga*-infested and non-infested plots were arranged in such a way that *Striga*-infested blocks were placed back-to-back in strips with non-infested blocks across the field. This arrangement reduced the movement of *Striga* seeds into the non-infested plots. Apart from *Striga* infestation, management practices were the same for both infested and non-infested plots. Fertiliser application was delayed until about 30 days after planting when 30 kg ha^{-1} each of N, P, and K were applied. Weeds other than *Striga* were controlled by hand weeding.

Observations were recorded on days to anthesis and silking as number of days from planting to the day that 50% of the plants in a plot had shed pollen and extruded silk, respectively. Anthesis-silking interval (ASI) was computed as the difference between days to 50% silk and anthesis.

Plant height was measured as the distance from the base of the plant to the node bearing the flag leaf and ear height, as the distance from the base of the plant to the height of the node bearing the topmost or only ear. The number of ears per plant (EPP) was calculated as the total number of ears at harvest divided by total number of plants at harvest in a plot. Plant aspect (PASP) was recorded on a scale of 1 to 5 based on overall plant type; where 1 = excellent plant type and 5 = poor plant type. Husk cover was rated on a scale of 1 to 5; where 1 = husks tightly arranged and extended beyond the ear tip and 5 = ear tips exposed. Ear aspect (EASP) was based on a scale of 1 to 5, where 1 = clean, uniform, large, and well-filled ears and 5 = ears with undesirable features. The factors considered in scoring ear aspect included ear size, uniformity of size, colour and texture, grain filling, and insect or disease damage. Plant aspect is the assessment of the general architecture of the plants in a plot as they appeal to sight and was rated on a scale of 1-5 under *Striga*-free conditions; where 1 = excellent plant and 5 = very poor (Badu-Apraku *et al*., 2011b).

In addition to these traits, host plant damage syndrome rating (Kim, 1991) and emerged *Striga* counts (STC8 and STC10) were taken at 8 and 10 weeks after planting (WAP) (56 and 70 DAP) in the *Striga*–infested plots. *Striga* damage syndrome ratings (STR8 and STR10) were scored per plot on a scale of 1–9; where 1 = no damage, indicating normal plant growth and high resistance, and 9 = complete collapse or death of the maize plant, i.e., highly susceptible (Kim, 1991).

Analysis of variance (ANOVA) was performed separately for data collected across years and locations for each of *Striga*-infested and non-infested environments. Combined ANOVA was also carried out using PROC GLM procedure in SAS (SAS, 2002). In the combined ANOVA, the location, year, replicates, and entries (30 hybrids and 2 checks) were considered as fixed factors.

HA-GGE biplot ("Scale=2") proposed by Yan and Holland (2010) was used for the evaluation of the genotypes performance as well as test environments. In addition, trait-association and trait-profile analyses (Yan *et al*., 2000; Yan, 2001; Yan and Rajcan, 2002; Badu-Apraku and Akinwale, 2011; Badu-Apraku *et al*., 2010a, 2011b) were performed using the GGE biplot software. Since the traits were measured in different units, the data were standardised using standard deviation method ("Scale= 1"), not transformed ("Transform= 0") and trait-centered ("Centering= 2"). Therefore, the outputs are appropriate for visualising the relationships among genotype and traits.

The entry/tester ("mean-vs-stability") view of the GT biplot were based on the selected traits (YIELD, EPP, STR8, STR10, STC8, STC10, and EASP) identified as reliable under artificial *Striga* infestation (Badu-Apraku *et al*., 2010a; Badu-Apraku and Akinwale, 2011) and under optimal growing conditions (YIELD, EPP, PASP, EASP, ASI, and PLHT). Equal weights were attached to the selected traits. The traits, PASP, EASP, and ASI, which are usually negatively correlated to YIELD and EPP, were re-scaled such that large values for these traits were desirable. This resulted in all the selected traits falling on one side of the ATC ordinate, thus meeting the requirement for valid conclusions on the "mean-vs-stability" view of the GT biplot (Yan *et al*., 2007).

RESULTS AND DISCUSSION

Analysis of variance revealed significant mean squares for location, year and genotype for all traits, except location mean squares for EPP, ASI, and STR10; year mean squares for EPP and STR10; and genotypic mean squares for SL under artificial *Striga* infestation (Table 2). Also, mean squares for year-by-location were significant for all traits. However, location x genotype, year x genotype, and location x year x genotype interactions were not significant ($P>0.05$) for most traits. Under *Striga*-free conditions, mean square value for location was significant for all traits except EPP, ASI, and PASP. Mean squares value for year was also significant for all traits except PASP; while genotypic mean squares were significant for all traits except SL (Table 3). Mean squares for year x location were significant for all traits, except EPP and PLHT. However, genotype x location, genotype x year, and genotype x location x year mean squares were not significant for most traits (Table 3).The significant genotypic mean squares observed for most *Striga* adaptive traits such as *Striga* damage ratings and number of emerged *Striga* plants indicated that even though the hybrids were all *Striga* resistant, the levels and/or mechanism of resistance may not be the same. Significant mean squares for locations under the *Striga* infested and non-infested research conditions implied that the two test locations were distinct and provided unique important information on the hybrids.

Combined ANOVA across infested and non-infested conditions showed significant means for all main effects, and non-significant interaction mean squares for most traits (Table 4). The significant *Striga* treatment-by-genotype interaction implies that even though, genotype x environment interaction components were not significant, there was differential response of the genotypes to *Striga* infestation and *Striga*-free conditions and that their performance ranking under *Striga* infestation was not the same with the ranking under *Striga*-free conditions.

Table 5 presents percent contributions of each component of variation relative to total sum of squares (SS) among the genotypes. It is evident that, the contribution of year SS for grain yield was much higher than those of location and genotype. In addition, location and genotype x year sum of squares had the highest contribution to GEI (Table 5). These indicate that the year effect greatly influenced the performance of the genotypes in the different locations.

GGE biplot analyses. Results of the HA-GGE biplot for data combined across infested and non-infested conditions are presented in Figures 1 to 5. In the polygon view of the biplot (Fig. 1), hybrids at the vertex of the polygon are considered as the best for the environments inside the sector. Thus, H27 (TZEI 11 x TZEI 25) was the

TABLE 1. Description of the hybrids and checks used in this study

Code	Hybrid	Reaction of inbred parents to *Striga* †	Grain colour
H1	TZEI 2 x TZEI 83	HR x T	White
H2	TZEI 2B x TZEI 60	HR x MR	White
H3	TZEI 11 x TZEI 12	HR x MR	Yellow
H4	TZEI 11 x TZEI 14	HR x HR	Yellow
H5	TZEI 11 x TZEI 23	HR x HR	Yellow
H6	TZEI 12 x TZEI 14	MR x HR	Yellow
H7	TZEI 12 x TZEI 23	MR x HR	Yellow
H8	TZEI 14 x TZEI 23	HR x H R	Yellow
H9	TZEI 2 x TZEI 80	HR x MR	White
H10	TZEI 188 x TZEI 2B	T x HR	White
H11	TZEI 2 x TZEI 21	HR x MR	White
H12	TZEI 2 x TZEI 2B	HR x HR	White
H13	TZEI 83 x TZEI 2B	T x HR	White
H14	TZEI 128 x TZEI 14	T x HR	Yellow
H15	TZEI 7 x TZEI 2B	MR x HR	White
H16	TZEI 106 x TZEI 2B	MR x HR	White
H17	TZEI 188 x TZEI 98	T x MR	White
H18	TZEI 2 x TZEI 81	HR x T	White
H19	TZEI 2 x TZEI 98	HR x MR	White
H20	TZEI 106 x TZEI 87	MR x MR	White
H21	TZEI 80 x TZEI 2B	MR x HR	White
H22	TZEI 136 x TZEI 11	HR x HR	Yellow
H23	TZEI 136 x TZEI 12	HR x MR	Yellow
H24	TZEI 136 x TZEI 14	HR x HR	Yellow
H25	TZEI 136 x TZEI 23	HR x HR	Yellow
H26	TZEI 11 x TZEI 127	HR x T	Yellow
H27	TZEI 11 x TZEI 25	HR x MR	Yellow
H28	TZEI 12 x TZEI 25	MR x MR	Yellow
H29	TZEI 23 x TZEI 25	HR x MR	Yellow
H30	TZEI 60 x TZEI 87	MR x MR	White
CHK1	TZE COMP4C3 (Resistant OPV)	Resistant	White
CHK2	8338-1 (Suseptible)	Susceptible	White

† HR = Highly resistant; MR = Moderately resistant; T = Tolerant

best hybrid under *Striga* infestation at Mokwa (MKS) and Abuja (ABS); while H28 (TZEI 12 x TZEI 25) was the best at Mokwa and H16 (TZEI 106 x TZEI 2B) at Abuja under *Striga*-free conditions. Figure 2 presents the entry/tester view of the HA-GGE biplot. The reduction in the proportion of the total variation explained by the principal component (PC)1 and PC2 (Fig. 2a) (86.5% when data were combined across years) and Figure 2b (70% when data were analysed for each year-location combination) indicated that the year has a confounding effect on the performance and ranking of the hybrids across locations. In these biplot displays, the thick single-arrow black line that passes through the biplot origin and the average environment is referred to as the average-tester axis (abscissa); the black arrow points to the average environment (small circle on the line) from the biplot origin and the entry's projection onto the abscissa approximated the yield performance of the hybrid. A vertical double-arrow line called the average-tester axis (ATC) ordinate divided the abscissa into two halves. Hybrids that fall on the right (positive) side yielded above average; while hybrids on the left (negative) side yielded below the average.

TABLE 2. Mean squares of grain yield and other agronomic traits of early maize hybrids with checks derived from combined ANOVA under *Striga* infestation at Mokwa and Abuja, Nigeria in 2008 and 2009

Source	DF	Grain yield (kg ha^{-1})	Ears per plant	Days to anthesis	Days to silking	ASI	Plant height (cm)	Stalk lodging (%)	*Striga* damage rating at 8 WAP	*Striga* damage rating at 10 WAP	*Striga* emergence count at 8 WAP	*Striga* emergence count at 10 WAP
Location (L)	1	7364455**	0.00931ns	103.8**	82.8**	1.1ns	51104**	356.3**	3.8*	2.1ns	873.9**	1795.6**
Year (Y)	1	50977626**	0.00003ns	167.4**	244.0**	13.6*	8707.2**	451.6**	16.5**	2.4ns	8201.6**	15656.3**
Hybrid (G)	31	3491125**	0.21431**	20.4**	20.3**	5.8**	1156.3**	4.5ns	5.1**	6.0**	821.0**	932.1**
Rep(L * Y)	4	4703687**	0.12784*	17.2**	19.3**	1.4ns	624.7ns	5.4ns	2.8*	0.1ns	186.9ns	367.0ns
L * Y	1	110861562**	0.28829**	640.7**	780.6**	10.9*	15515.8**	49.0**	32.3**	18.6**	25500.1**	41514.1**
G * L	31	823181ns	0.03596ns	2.6ns	5.1ns	2.6ns	454.1ns	7.7**	1.1ns	1.1ns	294.5ns	270.6ns
G * Y	31	974525ns	0.04043ns	3.1ns	6.4ns	3.4ns	438.5ns	4.7ns	1.7*	1.6ns	268.1ns	256.0ns
G * L * Y	31	1127431ns	0.03049ns	2.7ns	5.5ns	3.9ns	234.2ns	8.0**	1.1ns	1.0ns	337.6ns	485.3ns
Error	124	1129231	0.04616	2.6	4.9	2.6	303.1	3.4	1.1	1.1	335.7	383.1
Mean		2483.23	0.76	53.97	56.70	2.88	131.24	2.37	3.45	4.36	31.72	39.34
SE		531.33	0.11	0.81	1.11	0.81	8.70	0.92	0.52	0.53	9.16	9.79
R-Square		0.73	0.65	0.85	0.79	0.61	0.80	0.80	0.72	0.70	0.69	0.72

*,**, Significant F-test at 0.05 and 0.01 levels of probability, respectively

TABLE 3. Mean squares of grain yield and other agronomic traits of early maize hybrids with checks derived from combined ANOVA under *Striga*-free conditions at Mokwa and Abuja, Nigeria in 2008 and 2009

Source	DF	Grain yield (kg ha^{-1})	Ears per plant	Days to anthesis	Days to silking	ASI	Plant height (cm)	Ear height (cm)	Stalk lodging (%)	Plant aspect	Husk cover	Ear aspect
Location (L)	1	85713167**	0.02ns	256.0**	292**	0.9ns	16593**	8883**	6.6**	1.00ns	41.4**	7.9**
Year (Y)	1	196786971**	0.71**	311.0**	490**	20.3**	23620**	2093**	17.5**	0.06ns	1.7*	103.79**
Rep (L*Y)	4	3107234*	0.07**	25.0**	20**	1.3ns	292ns	283ns	1.0ns	1.32ns	0.1ns	1.54**
Hybrid (G)	31	5272315**	0.05**	19.0**	27**	2.8**	1759**	534**	0.5ns	1.60**	1.4**	1.60**
L* Y	1	55395363**	0.03ns	501.0**	659**	10.3**	653ns	3466**	11.0**	15.02**	2.8**	10.97**
G * L	31	867933ns	0.02ns	2.2ns	3ns	1.8*	288ns	146ns	0.7ns	0.48ns	0.8*	0.24ns
G * Y	31	1422450ns	0.02ns	3.5*	6*	1.9*	240ns	161ns	0.5ns	0.48ns	0.4ns	0.47ns
G * Y * L	31	923729ns	0.01ns	3.9**	4ns	1.0ns	294ns	158ns	0.5ns	0.41ns	0.6ns	0.50ns
Error	124	1086004.3	0.02	2.3	3	1.2	261ns	126	0.6	0.64	0.5	0.39
Mean		4346.4	0.9	53.9	56.1	2.2	160.7	77.5	0.5	4.3	4.9	4.4
SE		521	0.06	0.8	0.9	0.5	8.1	5.6	0.4	0.4	0.3	0.3
R-Square		82	64	88	87	65	79	75	60	59	72	82

*,**, Significant F-test at 0.05 and 0.01 levels of probability, respectively

TABLE 4. Mean squares of grain yield and other agronomic traits of early maize hybrids with checks derived from ANOVA combined across *Striga*-infested and *Striga*-free conditions at Mokwa and Abuja, Nigeria in 2008 and 2009

Source	DF	Grain yield (kg ha^{-1})	Ears per plant	Days to anthesis	Days to silking	ASI	Plant height (cm)	Stalk lodging (%)	Ear aspect
Location (L)	1	76769335**	0.03ns	334.8**	318.5**	0.2ns	62260**	132.0**	10.23**
Year (Y)	1	230322680**	0.36**	450.0**	758.0**	42.8**	30074**	321.9**	100.96**
Rep(L * Y)	4	6732312**	0.10**	41.8**	39.0**	1.1ns	673*	5.1ns	1.57
STRT[#]	1	487449204**	4.11**	1.3ns	111.0**	87.8**	118889**	461.3**	52.87*
Hybrid (G)	31	5610312**	0.18**	37.1**	41.2**	7.1**	2221**	3.0ns	3.04**
L * Y	1	164075840**	0.05	1194.38	1476.06**	21.16**	11381.63	7.0	21.81ns
G * L	31	1150769ns	0.03ns	4.0**	6.8**	3.0**	581**	4.7ns	0.58ns
G * Y	31	1283238ns	0.03ns	5.9**	10.9**	3.8**	429*	2.5ns	0.72ns
G * STRT	31	2906526**	0.08**	1.1ns	2.9ns	1.8ns	522**	1.9ns	0.94**
G * L * Y	31	1093478ns	0.02ns	4.9**	7.0**	3.1**	361ns	4.3ns	0.67*
Error	348	1174426	0.03	2.0	3.5	1.8	287	3.6	0.60ns
Mean		3467	0.85	54	56	2.5	147	1.42	4.6
SE		541.85	0.09	0.71	0.93	0.66	8.47	0.95	0.39
R-Square		0.77	0.57	0.84	0.80	0.53	0.78	0.54	64.00

*,**, Significant F-test at 0.05 and 0.01 levels of probability, respectively; [#] STRT = *Striga* infestation treatment

TABLE 5. Percent sum of squares of various sources of variation to the total sum of squares for grain yield and other agronomic traits of early maize hybrids and the checks

Source	DF	Grain yield (kg ha^{-1})		EPP		Days to silk		STR8	STR10	STC8	STC10
		I[¶]	NI[#]	I	NI	I	NI	I	I	I	I
Rep (LOC*Year)	4	20.5	1.7	40.3	4.6	21.8	2.5	33.2	40.0	19.5	17.2
Location (L)	1	1.4	11.5	0.1	0.3	2.9	9.2	0.8	0.4	0.7	1.1
Year (Y)	1	9.7	26.3	0.0	11.4	8.4	15.5	3.4	0.5	6.3	9.3
Hybrid (G)	31	3.6	21.8	3.1	22.6	2.7	26.0	2.3	0.1	0.6	0.9
G * Env[#]	94	38.2	20.7	21.8	24.8	44.8	33.5	31.8	29.2	41.0	43.3
L * Y	1	55.0	35.7	8.0	2.0	60.3	62.1	21.2	13.7	47.7	57.0
G * L	31	12.7	17.4	31.0	32.0	12.1	9.3	22.1	25.3	17.1	11.5
G * Y	31	15.0	28.4	34.8	38.2	14.9	17.2	35.0	37.6	15.6	10.9
G * Y * L	31	17.3	18.5	26.2	27.8	12.8	11.4	21.7	23.4	19.6	20.6
Error	124	26.6	18.0	34.7	36.4	20.6	13.4	28.5	29.7	31.9	28.2

[¶] I= *Striga*-infested; [#]NI = *Striga*-free conditions; [#]Env = Location-year combination

Projection of the hybrid's label onto the ATC ordinate approximated the stability of the hybrid. The longer the projection, the less stable the hybrid across infested and non-infested environments. Thus, TZEI 12 x TZEI 25, TZEI 11 x TZEI 25, TZEI 11 x TZEI 127, TZEI 136 x TZEI 11, TZEI 188 x TZEI 98, and TZEI 136 x TZEI 23 were identified as high yielding and very stable across both *Striga*-infested and *Striga*-free environments. Figures 3a and 3b showed the relationships among the test environments and were used for the evaluation of the usefulness of the test locations. In the context of HA-GGE, the length of the vector is a direct measure of the square root of the heritability of yield of a location (Yan and Holland, 2010), and is the appropriate measure of the value of a test environment (Allen *et al*, 1978). The vector length of the location label approximated its discriminating ability, while the cosine of the angle between any two vectors measured the genetic correlation between the two locations. The projection of the test environment onto the average environment (represented by small circle with an arrow pointer) is an overall measure of the usefulness of a test environment (Allen *et al*., 1978). Thus, in the biplot view in Figure 3a, the *Striga*-infested environments were grouped together and were separated from the non-infested environments. The correlations among the two locations were higher under *Striga*-infested than under *Striga*-free conditions. The presence of noncrossover interactions between the two research conditions was a clear indication of the effectiveness of the artificial infestation method used in the experiment.

The relatively long vectors of the environments under both research conditions indicated that the two environments possessed high discriminating power and that under *Striga*-infestation, Mokwa had greater discriminating power than Abuja. Furthermore, the high correlation between Mokwa under *Striga*-free conditions and the average environment axis implied that it is the most representative and most useful for evaluating the set of hybrids in the four environments.

The biplot in Figure 3b revealed the effect of years on the discriminating ability of the test locations even though the grouping of the

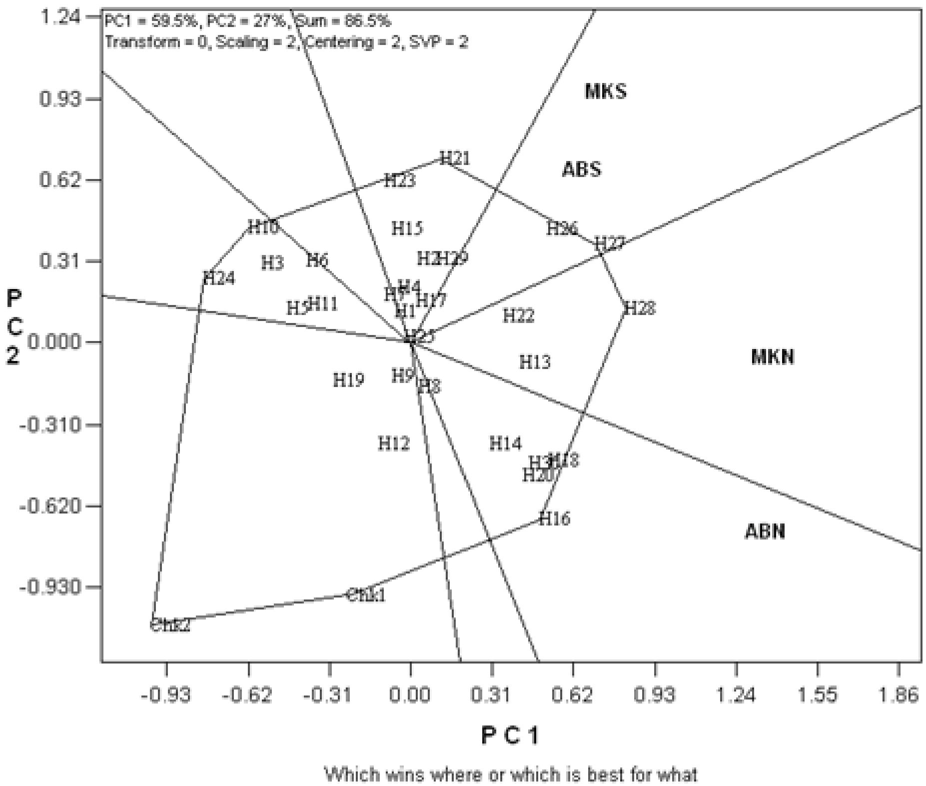


Figure 1. Polygon view of heritability-adjusted genotype main effect plus genotype-by-environment interaction (GGE) biplot showing which genotype is best for which environment.

environments was the same with that in Figure 3a. For instance, under *Striga*-infested conditions, the discriminating power of the locations in 2009 was higher than for year 2008; and the effect was more pronounced in Abuja than in Mokwa. Under *Striga*-free conditions, the year effect was generally less, but was more pronounced in Mokwa than in Abuja. Under *Striga*-free conditions, MK2N had the shortest projection onto the average environment axis, indicating that it is the most useful environment for evaluating the performance of the hybrids. Environments MK1 and MK2 had smaller acute angles between them than AB1 and AB2 under both study conditions, indicating that Mokwa showed higher repeatability than Abuja (Fig. 3b).

The ranking of the hybrids based on their yield performance and stability across environments under each research conditions is presented in Figure 4. The higher proportion of variation explained by the PC1 and PC2 of the GGE biplot under *Striga* infestation (90.4%, Fig. 4a) compared with that under *Striga*-free conditions (82.9%, Fig.4b) could be due to the fact that the hybrids used in the present study were selected from 378 hybrids based on their outstanding yield performance under *Striga* infestation in a diallel study.

In the biplot views of Figures 4a and 4b, genotypes within the innermost concentric circles were considered the ideal because they were high yielding and very stable across environments. Based on this, fifteen hybrids yielded above average under *Striga*-infested conditions; while thirteen yielded above average under *Striga*-free conditions. Under *Striga*-infested environments, H28 (TZEI 12 X TZEI 25), H21 (TZEI 80 x TZEI 2B), H26 (TZEI 11 x TZEI 127), and H23 (TZEI 136 x TZEI 12) were the closest to the ideal genotype (Fig. 4a) and H30

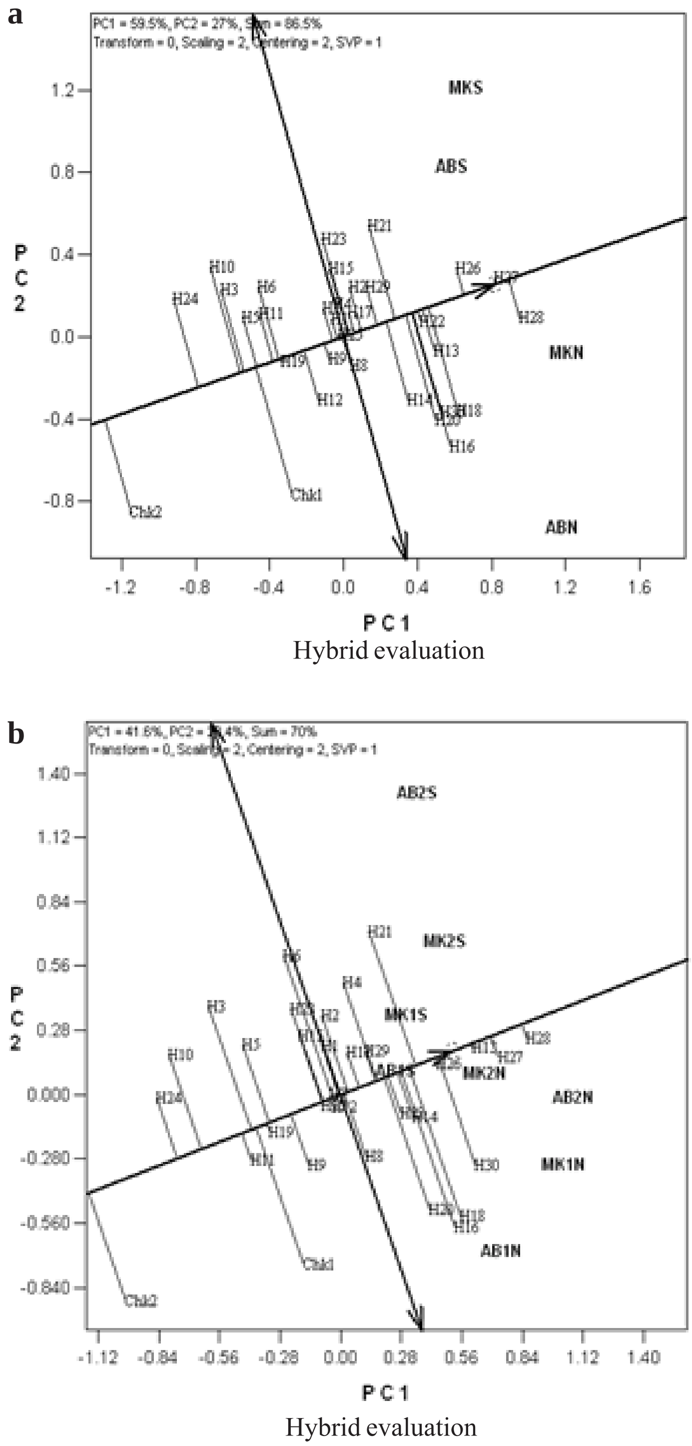
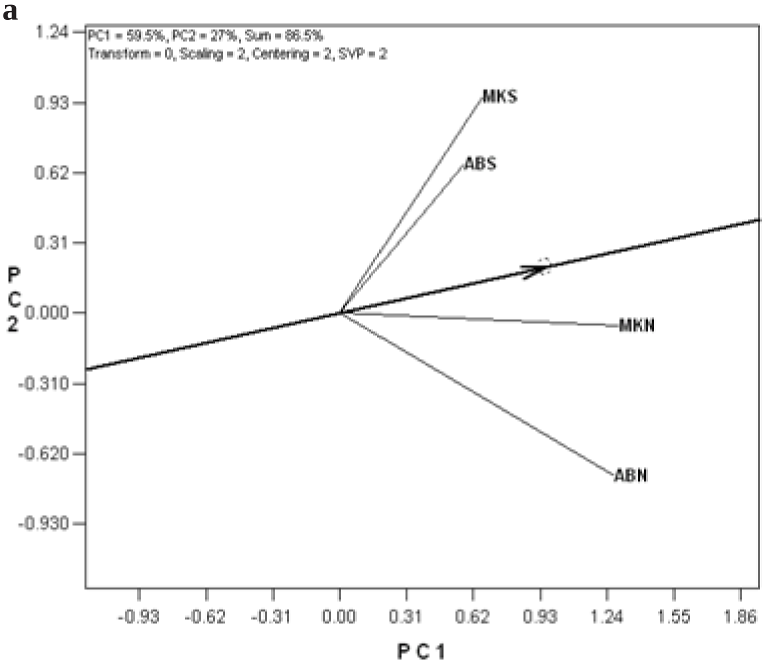


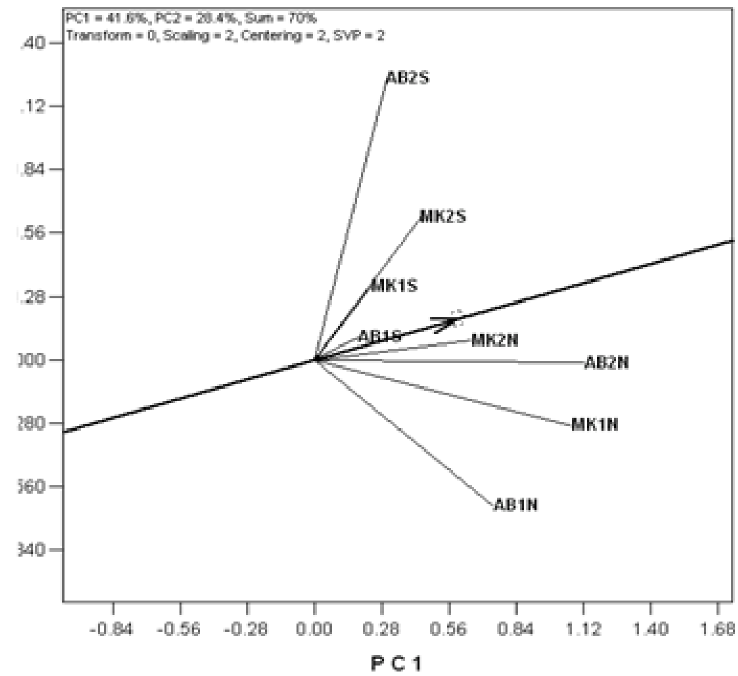
Figure 2. An entry/tester view of the HA-GGE biplot showing hybrid performance across *Striga*-infested and *Striga*-free conditions (a) data combined across years and replicates; (b) data combined across replicates only. Abbreviations; MKS for Mokwa under *Striga* infestation, ABS for Abuja under *Striga* infestation, MKN for Mokwa under *Striga*-free conditions, ABN for Abuja under *Striga*-free conditions, 1 stands for year 2008 and 2 for year 2009. See Table 1 for codes of hybrids.

a



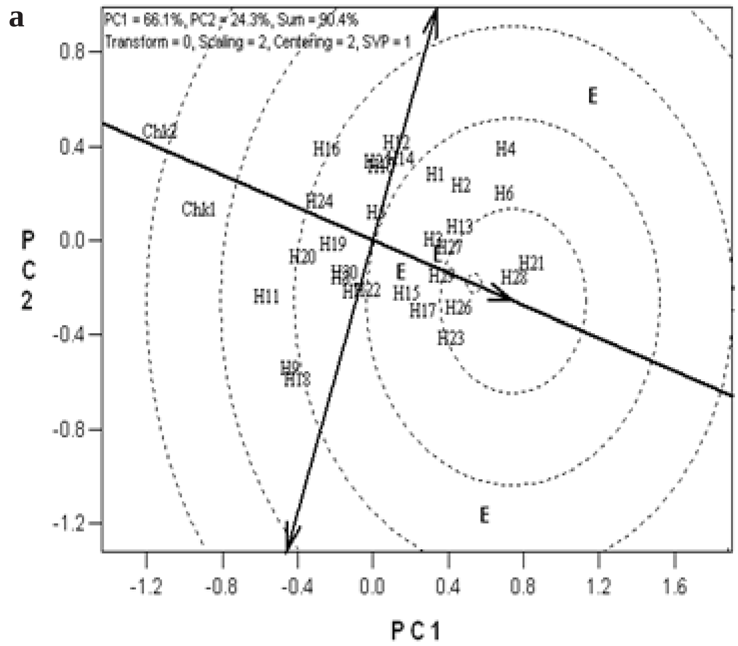
Test environment evaluation

b

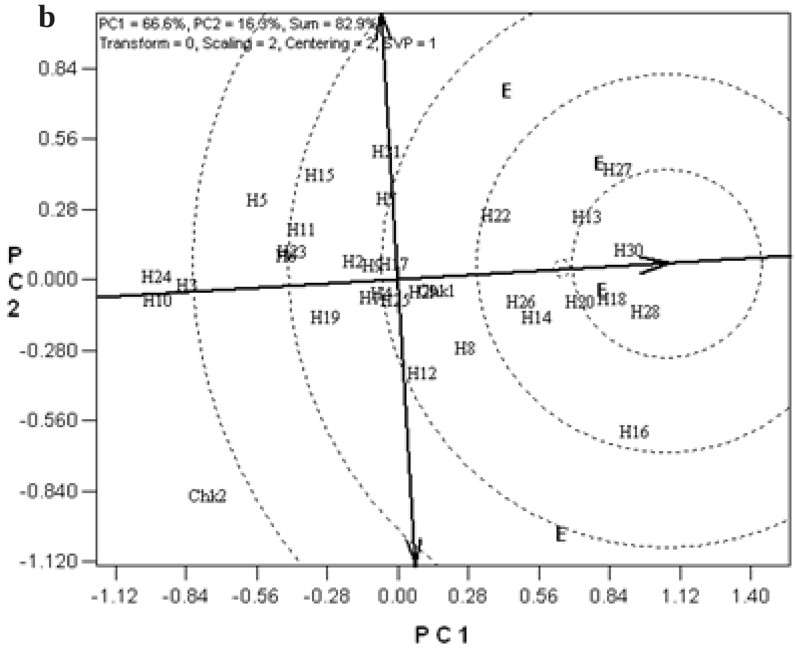


Test environment evaluation

Figure 3. Average tester coordination view of the GGE biplot showing the discriminativeness and representativeness of the test environments (a) Evaluation of test locations across years; (b) Evaluation of test locations in each year. Abbreviations; MKS, Mokwa under *Striga* infestation, ABS, Abuja under *Striga* infestation, MKN, Mokwa under *Striga*-free conditions, ABN, Abuja under *Striga*-free conditions; 1 stands for year 2008 and 2 for 2009.

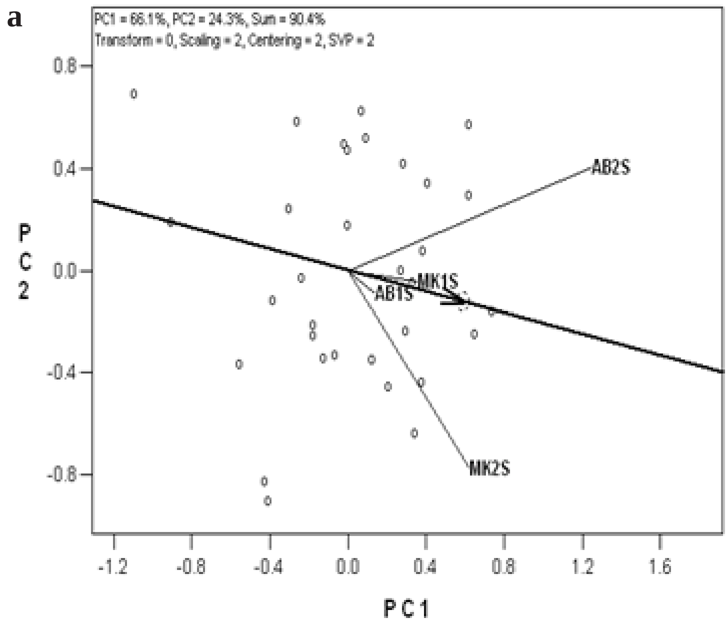


Ranking entries based on both mean and stability

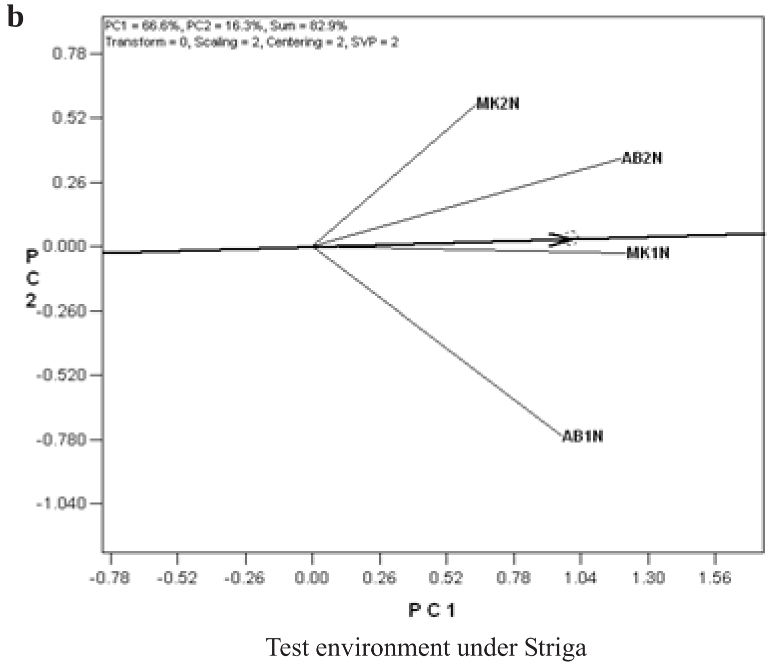


Ranking entries based on both mean and stabilit

Figure 4. Average tester coordination view of HA-GGE biplot showing the ranking of hybrids based on yield performance (a) under *Striga* infestation; (b) under *Striga*-free conditions. 'E' marked the exact position of the environments used for the ranking of the genotypes. See Table 1 for codes of hybrids.



Test environment under Striga



Test environment under Striga

Figure 5. Average tester coordination view of the GGE biplot showing the discriminativeness and representativeness of the test environment (a) under *Striga* infestation; (b) *Striga*-free conditions. Abbreviations; MKS, Mokwa under *Striga* infestation, ABS, Abuja under *Striga* infestation, MKN, Mokwa under *Striga*-free conditions, ABN, Abuja under *Striga*-free conditions, 1 stands for year 2008 and 2 for 2009.

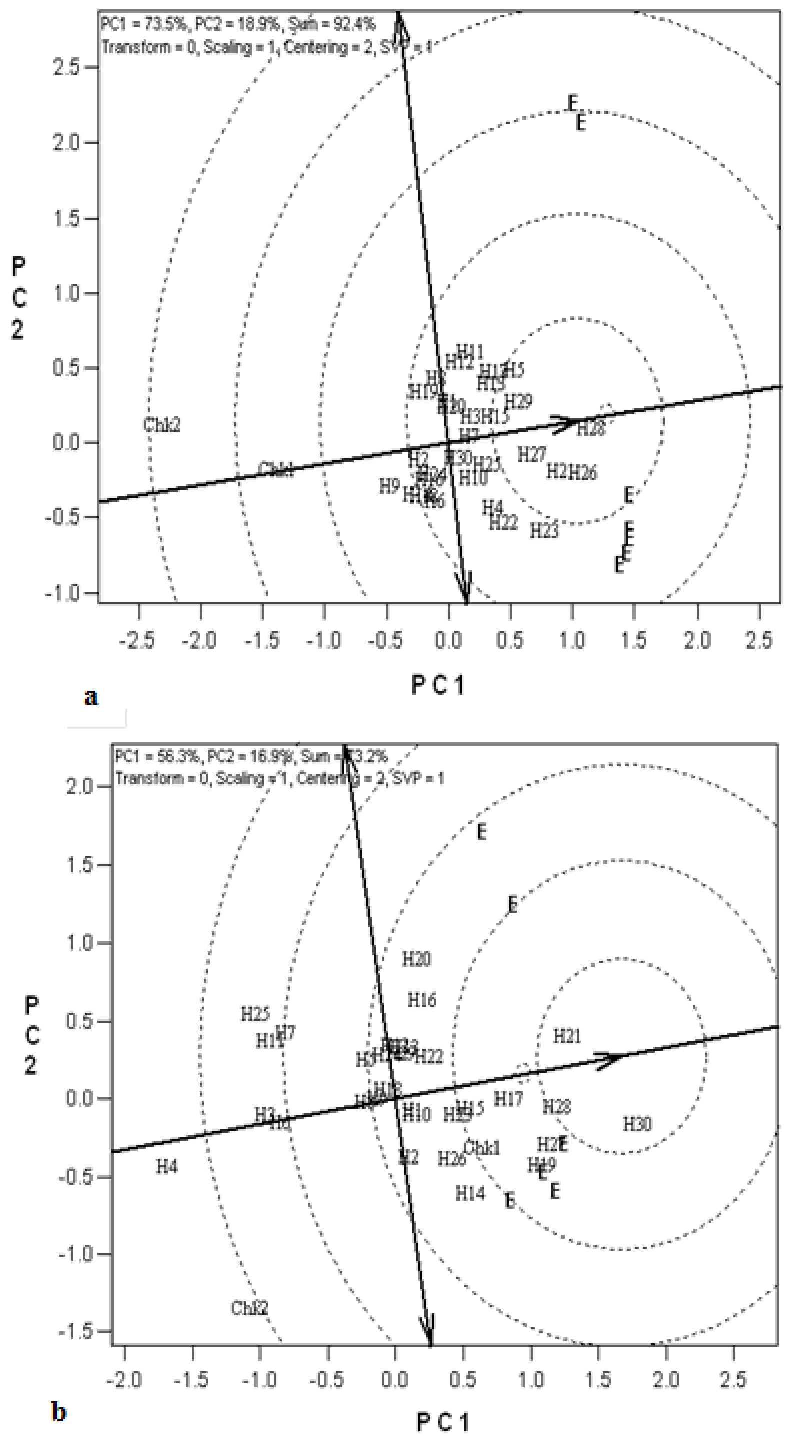


Figure 6. An entry/tester view of the GGE biplot showing the ranking of hybrids based on multiple traits under (a) *Striga* infestation and (b) *Striga*-free environments. Ideal genotypes are located inside the innermost concentric circle. 'E' marked the exact position of the traits used for the ranking. See Table 1 for codes of hybrids.

(TZEI 60 x TZEI 87), H18 (TZEI 2 x TZEI 81), and TZEI 12 x TZEI 25 under *Striga*-free conditions (Fig. 4b).

These results were in agreement with the findings of Badu-Apraku *et al*. (2010a), who identified TZEI 11 among four ideal inbreds under *Striga* infestation. Similarly, Badu-Apraku *et al*. (2011a) identified TZEI 11 as the best mating partner of seven out of nine yellow inbreds in a diallel study, indicating that it possessed high general combining ability under *Striga* infestation. The positions of the hybrids on the two biplots relative to that of the checks showed clearly that the hybrids possessed relatively higher levels of *Striga* resistance than the checks.

Figure 5 presents the discriminativeness and representativeness of the test locations under *Striga*-infested and *Striga*-free conditions. From the biplots, all locations/environments under *Striga*-infested and *Striga*-free conditions had angles less than 90^{o} among them (i.e., had positive correlations), confirming that the two test locations are related and belong to the same mega-environment. The high discriminating power of AB2S and MK2S and the low correlation between them (Fig. 5a) indicated that the two locations were distinct and provided useful information on the hybrids under *Striga*-infested conditions. None of the two locations could be considered as redundant.

The biplot also revealed that the locations in year 2008 were less discriminating than in year 2009. On the other hand, Figure 5b showed that the locations possessed relatively high discriminating power and that MK1N was most representative and most useful (high genetic correlation with average environment axis) under *Striga*-free conditions; whereas AB1N was the least representative and least useful for evaluating hybrid performance under *Striga*-free conditions.

The biplot in Figure 6a was constructed based on the traits identified as reliable for selecting *Striga*-resistant genotypes; whereas Figure 6b was based on traits reliable for selecting for improved grain yield under *Striga*-free conditions. About 70% of the hybrids performed above average under *Striga*-infestation, and 63% under *Striga*-free conditions. Similarly, the biplots showed that the hybrids were all *Striga*-resistant. An ideal entry (hybrid) in a GT biplot is described as the entry with the longest projection onto the ATC abscissa and positioned closest to the ideal entry (innermost concentric circle with an arrow in Fig. 6) (Yan *et al*., 2007; Badu-Apraku *et al*., 2010a). This implies that an ideal entry under *Striga* should combine many *Striga* adaptive traits in its genetic make-up. Thus, TZEI 12 x TZEI 25, TZEI 11 x TZEI 127, TZEI 80 x TZEI 2B, TZEI 11 x TZEI 25, TZEI 23 x TZEI 25, and TZEI 11 x TZEI 23 were the ideal hybrids under *Striga* infestation (Fig. 6a) while TZEI 80 x TZEI 2B, TZEI 12 x TZEI 25, and TZEI 60 x TZEI 87 were the ideal hybrids under *Striga*-free conditions.

CONCLUSION

Significant location effects under the two research conditions indicate that the locations are distinct from each other. The heritability-adjusted GGE (HA-GGE) biplot based on yield *per se* data reveal four hybrids as ideal under *Striga* infestation and three under *Striga*-free conditions. In contrast, multiple trait, standard deviation-standardised genotype-by-trait (GT) biplot analysis identify six ideal hybrids under *Striga* infestation and three under *Striga*-free conditions. Although, the two locations possesse high discriminating ability and neither of them could be considered as redundant, Mokwa possesses high repeatability and is more representative than Abuja. The use of multiple traits selection resulted in the identification of more promising genotypes under *Striga* infestation than selection based on yield *per se* performance, suggesting that grain yield alone is not a precise predictor of *Striga* resistance. Based on both HA-GGE and GT biplot analyses, TZEI 12 x TZEI 25 is outstanding in performance under *Striga*-infested and *Striga*-free conditions. Furthermore, TZEI 11 x TZEI 127 and TZEI 80 x TZEI 2B based on the two biplot methods are superior under *Striga*-infested conditions and TZEI 60 x TZEI 87 under *Striga*-free conditions. Hybrids TZEI 12 x TZEI 25, TZEI 11 x TZEI 127, TZEI 80 x TZEI 2B, and TZEI 60 x TZEI 87 with out- standing performance should undergo further testing and released for commercial production.

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